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Hydrologic response to and recovery from differing silvicultural systems in a deciduous forest landscape with seasonal snow cover

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ABSTRACT

Hydrological consequences of alternative harvesting strategies in deciduous forest landscapes with seasonal snow cover have received relatively little attention. Most forest harvesting experiments in landscapes with seasonal snow cover have focused on clearcutting in coniferous forests. Few have examined alternative strategies such as selection or shelterwood cutting in deciduous stands whose hydrologic responses to harvesting may differ from those of conifers. This study presents results from a 31-year examination of hydrological response to and recovery from alternative harvesting strategies in a deciduous forest landscape with seasonal snow cover in central Ontario, Canada. A quantitative means of assessing hydrologic recovery to harvesting is also developed. Clearcutting resulted in increased water year (WY) runoff. This was accompanied by increased runoff in all seasons, with greatest relative increases in Summer. Direct runoff and baseflow from treatment catchments generally increased following harvesting, although annual peak streamflow did not. Largest increases in WY runoff and seasonal runoff as well as direct runoff and baseflow generally occurred in the selection harvest catchment, likely as a result of interception of hillslope runoff by a forest access road and redirection to the stream channel. Hydrologic recovery appeared to begin towards the end of the experimental period for several streamflow metrics but was incomplete for all harvesting strategies 15 years after harvesting. Geochemical tracing indicated that harvesting enhanced the relative importance of surface and near-surface water pathways on catchment slopes for all treatments, with the clearcut catchment showing the most pronounced and prolonged response. Such insights into water partitioning between flow pathways may assist assessments of the ecological and biogeochemical consequences of forest disturbance.
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1. Introduction

Numerous paired-catchment experiments have assessed streamflow response to forest harvesting (see Brown et al., 2005, along with a more recent review by Buttle, 2011). Increased streamflow following harvesting enhances the potential export of sediment, nutrients and contaminants from the forest ecosystem; therefore, knowledge of the hydrologic consequences of forest harvesting assists understanding their implications for water quantity and quality as well as site productivity (Hornbeck et al., 1993; Schelker et al., 2013). Studies have often examined clearcutting (Bosch and Hewlett, 1982; Stednick, 1996), but few have studied hydrological responses to alternative silvicultural systems such as selection (removal of single trees to create an uneven-aged forest stand) or shelterwood (removal of the existing forest stand in a series of cuttings to promote regeneration in the harvested areas under shelter of the remaining stand to create an even-aged forest) harvesting.

Most harvesting experiments in North America and elsewhere have also been in coniferous forests. Paired-catchment studies in North America reported by Bosch and Hewlett (1982) and Stednick (1996), supplemented by additional Canadian work (e.g. Hetherington, 1987; Jewett et al., 1995; Swanson and Rothwell, 2001; Buttle and Metcalfe, 2000), total 38 separate experiments. Of these, 23 had conifer forest, while 15 had (in part or in total) deciduous forest cover. Of the latter, only 5 experiments had a significant (>10%) snowfall component of annual precipitation: Hubbard Brook, NH (Hornbeck et al., 1997; Martin et al., 2000), Marcell, MN (Verry et al., 1983; Verry, 1987), Leading Ridge, PA (Hornbeck et al., 1993), Nashwaak, NB (Jewett et al., 1995), and Streeter Basin, AB (Swanson and Rothwell, 2001). A similar

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situation exists in Europe, where a review of forest management impacts on peak flows and baseflows found only a single study of harvesting effects in a broadleaf forest landscape with seasonal snow cover (Robinson et al., 2003). Hydrologic consequences of forest harvesting in deciduous stands should be examined separately from those in coniferous forests, since the latter may use water throughout the year (provided temperatures and soil moisture are not limiting) whereas transpiration from the former is largely restricted to the leaf-on period (Jones and Post, 2004).

Harvesting of coniferous and deciduous stands may also differentially impact snow accumulation and melt (Jones and Post, 2004), which is particularly relevant in regions with seasonal snow cover. Resilience of runoff from deciduous forest ecosystems (i.e. stable and/or predictable annual runoff in the face of changing environmental conditions such as precipitation and evapotranspiration) may also differ from that of coniferous forests (Carey et al., 2010; Creed et al., 2014). This highlights the need to consider the distinct hydrologic response of deciduous forests to harvesting under changing climatic conditions.

Sustainable management of deciduous forests with seasonal snow cover would benefit from knowledge of ecosystem response to various silvicultural systems and any subsequent hydrologic recovery. Hydrologic recovery is the restoration of hydrologic characteristics to near pre-disturbance conditions via forest regeneration after either natural or anthropogenic disturbance (Hudson, 2000). Previous work has often been in temperate landscapes where forest regrowth rates and hydrologic recovery may be more rapid than in more northerly landscapes (e.g. Buttle et al., 2005). Thus, further study of hydrologic recovery in deciduous forests in colder climates is needed.

Research into hydrologic response to and recovery from harvesting in deciduous forests with seasonal snow cover should also consider changes in water flow paths, which may be associated with shifts in the partitioning of precipitation between high and low flows as well as altered nutrient and contaminant fluxes from the catchment. Forest harvesting may increase the proportion of runoff reaching streams via rapid flow pathways such as saturation overland flow and near-surface lateral flow (e.g. Caissie et al., 2002; Waterloo et al., 2007). This would presumably accompany more net precipitation entering the soil following forest canopy removal, enhanced soil wetness and expansion of surface saturated areas. Increased water recharge following forest harvesting could also augment groundwater discharge to streams (Buttle, 2011). Therefore assessment of the biogeochemical consequences of forest harvesting would benefit from information regarding any associated changes to water flow pathways.

This paper presents the results of a long-term (31 year) examination of hydrological response to a range of forest silvicultural systems in a deciduous forest landscape with seasonal snow cover. We present a quantitative approach to assessing hydrologic recovery for these silvicultural systems, and examine changes in water flow pathways following harvesting. The paper's specific objectives are to:

1. determine whether different silvicultural systems (clearcut, shelterwood and selection) have produced significant changes in a range of catchment streamflow metrics;
2. assess the degree of hydrologic recovery for each metric in the time since harvesting; and
3. test the hypothesis that harvesting has increased the relative importance of surface and near-surface flowpaths for water delivery to streams.

These objectives provide the structural subheadings used in the following Sections 3–5.

2. Study site. Silvicultural treatments, and experimental design

2.1. Study site

The study was conducted at the Turkey Lakes Watershed (TLW; 47°03′N, 84°25′W), ~60 km north of Sault Ste Marie, Ontario (Fig. 1) in the Great Lakes – St. Lawrence forest region (Rowe, 1972) of the Boreal Shield Ecozone in the Algoma region of central Ontario. The TLW has a total relief of ~300 m. Mean daily air temperature at the TLW (1980–2010) is 4.6 °C, with mean daily January and July air temperatures of −10.7 and 17.9 °C, respectively (Semkin et al., 2012). Mean annual precipitation is 1189 mm (Semkin et al., 2012), of which 35% falls as snow (Beall et al., 2001). Snow cover begins to develop in late October and melts during the March–May period. Mean annual runoff in the TLW is ~ 400 mm (OMNR, 1984). Regional bedrock is Precambrian metamorphic basalt (silicate greenstone) with some granitic outcrops, covered by thin discontinuous two-component till: bouldery silt loam ablation till overlying compacted sandy loam basal till (Hazlett et al., 2001). Hillslope soil cover is orthic humo-ferric podzols (spodosols) with well-defined L and F (Oi and Oe) horizons with a combined average thickness of 0.05 m (Hazlett et al., 2001), while dispersed organic soils occupy depressions and riparian areas (Creed et al., 2008). The TLW has a mature shade-tolerant hardwood forest cover of sugar maple (*Acer saccharum* Marsh., 90%), yellow birch (*Betula alleghaniensis* Britton; 9%), and various conifers (1%) (Jeffries et al., 1988). The TLW is undisturbed, with the exception of a light selective harvest ("high-grading") in the 1950s (Beall et al., 2001) and the experimental harvest in 1997 that is the focus of this study.

2.2. Silvicultural treatments and streamflow measurements

In the late Summer and Fall of 1997 catchments within the TLW were harvested using differing silvicultural systems followed by natural stand regeneration. A before-after control-impact (BACI) paired-catchment approach was used to evaluate whether harvesting resulted in changes to catchment streamflow. Catchment characteristics for treatment and control catchments are given in Table 1. Control catchments were selected based on their similar size, morphology and proximity relative to a given treatment catchment. Data on pre- and post-harvest stocking, basal area and volume are given in Table 2. Mensuration data from c35 and c46 are not available; however, visual observations suggest forest cover in these catchments was similar to that in c32. Catchment c31 was "clearcut" using a diameter limit cut in which all trees >20 cm diameter were felled, de-limbed, and removed, and all trees 10–20 cm diameter were felled and left on site. Catchment c33 was harvested using single-tree selection, an uneven-aged system where mature and undesirable trees were removed. A forest harvest access road ran parallel to the stream in c33 for about 750 m, and runoff culverts were oriented toward the stream channel. An even-aged uniform shelterwood system was used in c34, where ~50% of mature trees were harvested with residual trees providing a shelter. This system requires a series of harvests for successful regeneration and stand development. Selection and shelterwood harvesting are accepted silvicultural systems used in shade-tolerant hardwood forests in Ontario (OMNRF, 2015); clearcut harvesting was undertaken to maximize hydrological and biogeochemical disturbance experimentally rather than to simulate actual commercial harvesting (Monteith et al., 2006). Selection and shelterwood harvesting left 64% and 61% of the pre-harvest overstory volume as live standing, compared to 22% for the clearcut harvest (Table 2).

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